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Final Technical Report
November 1996

ANALOG HARDWARE DESCRIPTION LANGUAGE (AHDL)

MTL Systems Inc.

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13. ABSTRACT (*Maximum 200 words*)
This report documents a project conducted by MTL Systems, Inc., Analogy, Inc., and Compass Design Automation. The project supported the development of an analog and mixed-signal variant of the digital VHSIC Hardware Description Language (VHDL), named "VHDL-AMS" (VHDL-Analog/Mixed-Signal). The purpose of the project was to assist, expedite, facilitate, and generally support the VHDL-AMS language development and standardization process being conducted by the Institute of Electrical and Electronic Engineers (IEEE). The report documents the experiences of the project team in assisting this standards development process, and may therefore be used as a case study of Government-sponsored language development within an open standards organization. The report first overviews the problem which was addressed, presenting the program goal and objectives and a succinct summary of the results which were produced. It next describes the language development and standardization process, first in a chronological narrative format and then through a summary of the challenges encountered and the results obtained. It finally presents specific conclusions and recommendations regarding how Government-funded standards development projects might be handled in the future, based upon the experiences, lessons learned and results of this program.

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Preface

This report describes a project entitled "Analog Hardware Description Language." The project was conducted for the USAF Rome Laboratory Design and Diagnostics Branch (RL/ERDD), from June, 1993 to January, 1996, under contract number F30602-93-C-0209. The effort was conducted by MTL Systems, Inc., Dayton, Ohio, with subcontract support from Analogy, Inc., Beaverton, Oregon, and Compass Design Automation, Inc., Silver Springs, Maryland. The Rome Laboratory Program Manager was Steve Drager. The MTL Principal Investigator was Robert Collins. Ernst Christen directed the Analogy subcontract efforts and Ken Bakalar coordinated the Compass support.

ANALOG HARDWARE DESCRIPTION LANGUAGE (AHDL)

Final Technical Report

1.0 INTRODUCTION

This document is the Final Technical Report (CDRL-A007) for United States Air Force (USAF) Rome Laboratory contract number F30602-93-C-0209, entitled "Analog Hardware Description Language (AHDL)." The program was conducted by MTL Systems, Inc. (MTL) as prime contractor, and Analogy, Inc. and Compass Design Automation (formerly CAD Language Systems Inc. (CLSI)) as subcontractors. The AHDL program was sponsored by the United States Air Force Rome Laboratory, Design and Diagnostics Branch (RL/ERDD). We would like to thank the RL/ERDD staff, and especially the RL Program Manager, Steve Drager, for their support in the course of this effort.

Herein, we document the contribution of the subject effort to the process of developing an analog and mixed-signal variant of the digital VHSIC Hardware Description Language (VHDL), named "VHDL-AMS" (VHDL- *Analog/Mixed-Signal*). The purpose of our effort was to assist, expedite, facilitate, and generally support the VHDL-AMS language development and standardization process being conducted by the Institute of Electrical and Electronic Engineers (IEEE). This report emphasizes the experiences of our project team in assisting this standards development process *via* Rome Laboratory (RL) sponsorship. It may therefore be used as a case study of RL-sponsored language development within an open standards organization, to assist future endeavors of this nature. In this report, we have not included specific technical information with respect to the VHDL-AMS language. Such language specifics may be reviewed in the other deliverables from this program, including the Language Requirements Document (CDRL-A004), the Language Rationale (CDRL-A005), and the Language Reference Manual or *LRM* (CDRL-A006).

Our report is organized into four principal sections. In this first section we provide an overview of the problem we addressed, including some background information. Here, we also present our program goal and objectives as well as a succinct summary of the results we produced. Next, in Section 2.0 we present the technical description of the language development and standardization process, first in a chronological narrative format and then through a summary of the challenges we encountered and the results we obtained. Here we cover, step-by-step, the twists and turns of the language development process. Then, in Section 3.0, we offer our conclusions and recommendations. From this information, the reader may assess how Rome Laboratory-funded standards developments might be handled in the future, based upon our experiences in this program. Finally, in Section 4.0, we acknowledge the

substantial support we were provided by many organizations and individuals. We now begin with our problem overview.

1.1 The Problem

The problem we addressed within this program was (and is) the need for a *standard description and simulation language for analog and mixed-signal (digital-analog) electronic design.* The changes in the content and complexity of electronic systems being designed today demand new design tools, and the consequential tool developments require a method for design representation, such as a hardware description language (HDL). Such a language would also provide support for non-electrical systems, for example thermal, hydraulic, rotational etc., as well as support for system-level designs.

Proprietary HDLs for analog and mixed-signal designs exist in various forms, such as SPICE. However, SPICE is considered to be a low-level HDL which encounters difficulties at other abstraction levels. Also, there are HDLs for purely digital design at multiple abstraction levels, such as VHDL. However, there are no *standard* languages supporting mixed-signal design at multiple abstraction levels. Hence, analog and mixed signal designs do not enjoy the benefits of effective, automated design support, as illustrated in Figure 1.1.

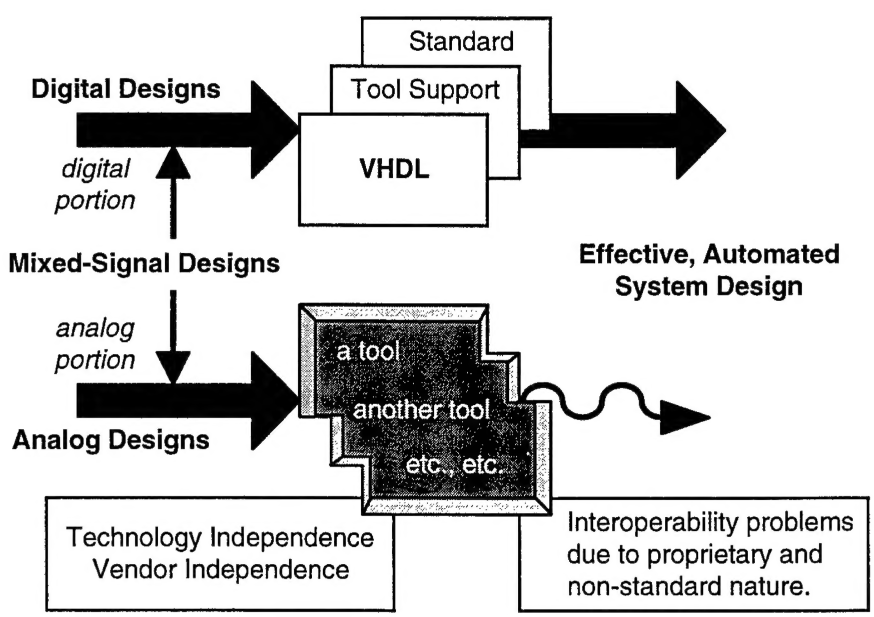

Figure 1.1: Lack of EDA Support for Analog and Mixed-Signal Design

There are three aspects of design content, for modern electronic systems, which are driving the need for new/modern/advanced mixed-signal design tools. First, there are many designs which tightly integrate analog and digital sections, such as in digital signal

processing (DSP) or electro-optical systems. Second, many digital designs are operating at very high frequencies wherein analog effects cannot be ignored. Third, it turns out that higher level abstractions of purely analog models often make use of event-driven (i.e., digital) concepts. One example is a bouncing ball, wherein the ideal model must manage the discontinuity that occurs when the ball is bounced. These changes in *design content* support the need for mixed-signal design tools.

Designers also have to deal with the tremendous complexity in modern system design. This complexity must be managed by designing at high levels of abstraction and compartmentalizing portions of the designs. Completing the design then also requires the lower abstraction levels to be defined and implemented. To address these problems in digital systems, design languages such as VHDL (IEEE 1076-1993) provide mechanisms to develop and simulate design descriptions covering multiple abstraction levels simultaneously. Similarly, in analog or mixed-signal designs, such tools must also provide this ability to support multiple abstraction levels.

While there are many design support tools to support either analog or digital development independently, there are very few that support mixed-signal design, and those that do are not compliant to an industry-wide standard to support widespread use and design exchange. The mixed-signal tools that are available use mostly proprietary design representation methods. The completion of the VHDL-AMS standard will solve the problems of non-standard, proprietary representations, to facilitate the development of new mixed-signal design tools.

Hence, the general problem was the need for a standard analog and mixed-signal HDL - *VHDL-AMS*. The specific challenge of this effort was to assist in the development of this HDL, given the complexity of providing this support within a process under the control of an external organization (the IEEE), and subject to the influence of an international design community. We now explore these external influences in more detail within our background discussions.

1.2 Background

Over the past two decades, computer-based electronic design automation (EDA) tools have moved from the research lab to be an integral tool for all but the very simplest designs. The earliest tools covered relatively small domains such as linear analog circuits. As the tools matured, the domains over which they were useful grew. Today, there are two major, but separate, domains for which there are tools:

1. The digital, or discrete, domain, and
2. The analog or continuous domain.

The separation between the two domains has historically been satisfactory or at least tolerable, but is rapidly becoming less so. Up to now, many electronic systems were

either completely digital or, if they were digital and analog, the separate domains could be developed independently. This allowed the designers to use digital design and simulation techniques to develop the digital portions and analog techniques for the analog portion. However, for contemporary designs where the two domains are more tightly integrated, the designer is faced with several unsatisfactory compromises. This, coupled with the digital occurrences in high-level continuous model abstractions, are the reasons to provide a unified language environment.

These compromises generally force the designer to constrain the use of a tool or settle for a non-optimal or unsharable design. For example, the designer could partition the design, run analog portions on an analog tool and digital portions on a digital tool, and then try to manually "glue" the results together. This is reminiscent of historical designs and forces the designer to settle for a less-than-optimal mixed-signal integration of the two domains. Alternatively, the designer could treat the entire design as analog, which, for most designs, would slow the tools down sufficiently to allow only partial simulation or testing. This can significantly constrain the effectiveness of the tool. Also, in some cases, the designer might represent the analog characteristics using digital tools. Again, this adaptation of one domain to another for which it was never intended can constrain its effectiveness. Finally, there are a few proprietary mixed-signal tools such as Analogy's Saber, but a user is subject to the usual design transfer and data sharing constraints wrought by non-standard environments.

For the last few years, an internationally-supported working group, (IEEE P1076.1) within the Design Automation Standards Committee of the IEEE Computer Society, has been developing the definition of a mixed-signal hardware description language (HDL) called VHDL-AMS. This HDL is an extension to VHDL (IEEE 1076-1993), which primarily addresses the digital domain. VHDL-AMS adds analog and mixed-signal capability through the definition of semantics to express the continuous-time behavior of conservative systems. This language definition is nearing completion and should be voted on later this year.

At the inception of this program, the Air Force recognized the need to assist and accelerate the VHDL-AMS standardization process. Due to the voluntary nature of the IEEE Working Group (heretofore referred to simply as “the WG”), providing resources would accelerate the language development. The resulting VHDL-AMS standard would enhance the effectiveness of analog and mixed-signal designs for military and commercial systems alike. This contract was conceived to be the method to achieve this assistance and acceleration, as illustrated in Figure 1.2. With a standard design language, the next step in the evolution of analog and mixed-signal electronic design, the automation tools, may now proceed.

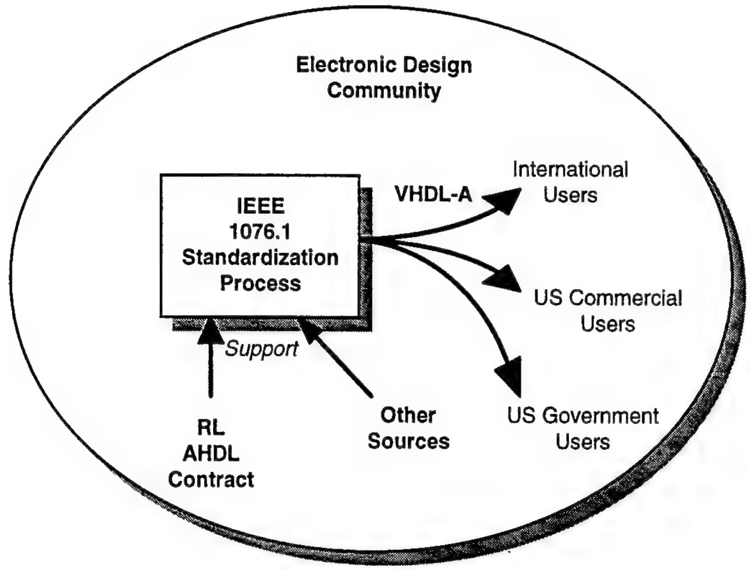

Figure 1.2: RL Support for the VHDL-AMS Standardization Process

In summary of this background, an analog and mixed-signal HDL was demanded by designers on an international scale. The benefit to the USAF and to government and commercial electronic systems designers at large would be the demanded, standard analog HDL and subsequent tools from commercial vendors based upon this standard. The IEEE had the standardization process started, and the USAF conceived this contract to provide valuable support. To accomplish this support, we set several program objectives which we describe next.

1.3 Goal and Objectives

In this section we review the goal of this effort, and the program objectives we established, for addressing the mixed-signal HDL problem within this effort. The overall goal of the AHDL program was to accelerate the definition of analog and mixed-signal extensions to VHDL, through coordination with, and support for, the IEEE standardization process, as we illustrate in Figure 1.3. The specific objectives, as listed in our proposal, were to:

1. Develop the VHDL-AMS definition (the LRM),
2. Coordinate with the IEEE for standardization, and
3. Mitigate risk (to ensure a usable, successfully-balloted standard).

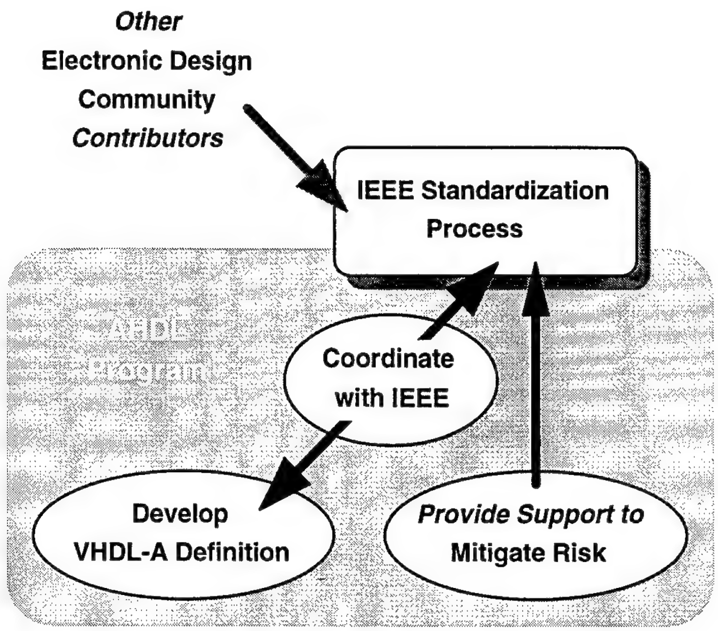

Figure 1.3: AHDL Contract Objectives Supporting the IEEE Standardization Process

One very important aspect of risk mitigation is trying to build consensus among the parties involved. In this sense, an early buy-in facilitates the development at later stages and considerably reduces the balloting risk. Hence, as we describe in Section 2.0, much of the early work was in fact devoted to this issue, to get people lined up. This is also why we wanted participants from all the major vendors involved in the language architecture definition process.

In the next section, we briefly summarize our results in the context of achieving these objectives. These results are more fully elaborated in Section 2.0, and their value assessed in Section 3.0.

1.4 Summary of Results

In this section we provide a quick summary of what was accomplished through the AHDL program.

With the funding provided by this effort, we were able to support highly-qualified, recognized domain experts to work on the language definition. As such, the language definition and standardization process was accelerated and will result in a better, more useful language design. This result was a significant contributor to achieving our objective (1) to develop the VHDL-AMS standard.

We also learned that, when developing a standard in an open environment with numerous participants such as the IEEE, any particular organization has only so much

influence and cannot, by itself, drive the process to conclusion. However, the AHDL Project Team contributed to the standardization process in many ways, as illustrated in Figure 1.4. The AHDL Project Team provided technical input to the LRM development process in many ways including development of: the Design Objectives Document (DOD), the Design Objective Rationale (DOR), and the majority of topical "White Papers" which will form the basis of the Language Reference Manual. Although the Standardization Committee has not yet agreed on the final definition to be asserted in the Language Reference Manual (LRM), we expect that the major differences will be resolved shortly and that there will be an IEEE standard by the end of 1996. Hence, we achieved our objective (2) to coordinate with the IEEE for standardization, and provided technical support to achieve our objective (3) to mitigate risk.

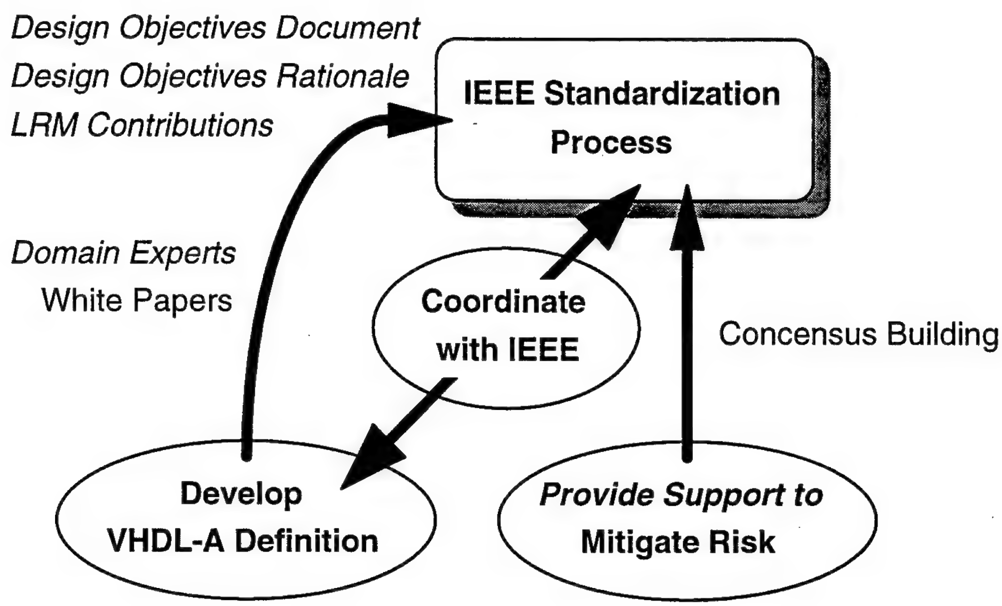

Figure 1.4: AHDL Program Contributions to the Standardization Process

In summary, we met, in part or in whole, the objectives we established. However, in reality, our coordination with the IEEE could have been more effective. It was a learning process, and we learned from it, as we describe next, in Section 2.0.

2.0 AHDL PROGRAM SUPPORT FOR THE LANGUAGE DEVELOPMENT PROCESS

In this section we review the VHDL-AMS development process in a chronological manner to provide the reader insight into the language development process, in the context of this effort. We begin with an introduction which defines the state of analog HDL development at the program's inception, and also outlines our approach. Then, we present the results of executing that approach, in a chronological sequence.

2.1 Introduction and Approach

To address the lack of a standard hardware description language for designing in a mixed-signal environment, MTL Systems, in early 1993, proposed a program to define a set of extensions to VHDL and submit the extensions for standardization. This was an outgrowth of the decision by the IEEE VHDL 1993 Standardization Committee to not address mixed-signal models within the base language. Our proposal, which included team members from Analogy, Inc. and CAD Language Systems, Inc. (CLSI), was accepted by Rome Laboratory and the program went on-line in June 1993.

Prior to this effort going on-line, an effort in Europe, funded by JESSI/ESPRIT, also got underway. The project had similar goals as those of the AHDL program. The European team members included representatives from universities, the CAD vendor AnaCAD, and several large companies (Bosch, French Telecom). This effort proceeded with minimal input from U.S.-based representatives with the notable exceptions of Kevin Nolan and Ernst Christen of Analogy, and Mark Brown of Compass, who was the IEEE (1076.1) Working Group Chair at the time this contract was awarded. All parties were working under the auspices of the IEEE as PAR1076.1 "Analog Extensions to VHDL," in what we will refer to as the "1076.1 Working Group" or simply the "WG", throughout this report.

The approach taken for this program was basically to *apply our USAF-funded resources to expedite and facilitate the language development and standardization process within the IEEE Working Group.* We planned to synchronize our effort to the IEEE standardization process, performing development tasks and producing documentation (Requirements Rationale, Language Rationale, Language Reference Manual) which would apply to both the IEEE standardization process needs and serve as deliverables under the AHDL contract. We expected to conduct AHDL project meetings in concert with IEEE 1076.1 Working Group meetings and EDA conferences such as the VHDL International User's Forum (VIUF) and the Design Automation Conferences (DAC, EuroDAC), to ensure coordination and to gain access to other industry and Working Group participants.

The approach was fundamentally well-conceived, but the coordination aspects proved to be more challenging than expected, as we shall describe in Sections 2.0 and 3.0. Now, having made this introduction and outlined our approach, we next describe the sequence of events that has led us to where we are today.

2.2 Language Development Chronology

The AHDL contract was funded on June 25, 1993, and MTL Systems immediately authorized our subcontractors to begin work. The subcontractors were Analogy, Inc. and Compass Design Automation (formerly CAD Language Systems, Inc. (CLSI), who were acquired by Compass just prior to the AHDL program's start). MTL was assured by Compass management that their acquisition of CLSI would in no way jeopardize the ability to staff and support the program as proposed.

MTL Systems' Program Manager (PM) and Principal Investigator (PI) was Mr. Raymond Wabler. He was assisted, principally regarding the more technical aspects of analog design and language development, by Ms. Wenying Zhou. Analogy's Principal Investigator was Dr. Ernst Christen and Compass Design Automation's PI was Mr. Mark Brown, who was assisted by Dr. Stanley Krolikoski.

In the chronology which follows, we first describe the initial 4-month period of the program, which brings us to the end of a fiscal quarter in the Government and MTL calendars. From that point onward, we describe events by quarters (3-month periods). The reader interested solely in how our contractual activities supported and facilitated the language development will find these aspects summarized in our introductions to each time period. However, in the detailed discussions for these periods, we include internal and external (to the contract) events which had any significant bearing upon the effort, to provide a comprehensive picture of the activities, challenges, and interactions which comprised this effort.

Although we include activities outside the contractual effort, for the sake of completeness, our focus is upon the AHDL Project Team's contribution to the overall VHDL-AMS language standardization process. In summary, the AHDL Team not only made the majority contribution to the technical concepts development (as technical white papers), but also mitigated disputes among WG members, and found solutions to both technical and coordination impasses, to keep the.entire standardization process moving forward. In the chronology which follows, we elaborate upon these aspects.

JUNE-SEPTEMBER, 1993

In this time period, we initiated the AHDL contract work, and began the process of coordination with the IEEE. We conducted the program Kickoff Meeting and began the task of integrating our effort with the IEEE standardization process. Here, we

liaisoned with the newly-formed Analog VHDL International organization to ensure effectively capturing their work into the process. We also began working with international members of the WG, to promote a cooperative and beneficial relationship, for the overall benefit of the standardization process. Additionally, we began the process of reviewing the existing Language Extension Specifications (LESs), which were the current mechanism for defining the language technical changes. The specific events and topics relevant to this period are listed below.

Kickoff Meeting: An AHDL program Kick-Off Meeting was held on 17 August 1993 at Rome Laboratory. The attendees included all the principal investigators (PIs) from MTL and our subcontractors, as well as Dr. Harold Carter of the University of Cincinnati as MTL's guest. We reviewed the program objectives and discussed external events influencing the development of VHDL-AMS

CLSI Staff Change: Mark Brown of CLSI left work on the contract due to other commitments. This was a major blow to our original plans as Mark's position as Working Group Chair was felt to be invaluable in driving the standard to completion. Not that all decisions had to be made by our team members, but the funding and schedule were fixed and having a Chair not driven by the same time constraints allowed for the possibility of this effort running out of time and money without a completed standard.

Analog VHDL International (AVI): At this time, AVI was a newly-formed organization conceived to coordinate and synergize the needs and efforts of disparate, international organizations interested in analog and mixed-signal extensions to VHDL. AVI consisted of CAD vendors (Cadence, Analogy, MetaSoftware and Compass Design Automation) and universities. Their charter was to support the IEEE effort to develop VHDL-AMS. Two AHDL team members held prominent positions in this organization: Stan Krolikoski (AHDL Team member) was the Chair and Ernst Christen (AHDL Team member) was Chair of the Validation Sub-Committee. Their planned efforts included development of a test suite for the 1076.1 standard VHDL-AMS, and a sample model standards library. Both the organization and its intended efforts were viewed as being complementary to both the standardization process and the AHDL contract effort, with the realization that AVI constituted yet another sphere of influence upon the standardization process which had to be dealt with.

MHDL (MMIC Hardware Description Language): We reviewed the ongoing work being done on this, primarily, microwave targeted HDL. Dave Williamson (RL/ERDA) presented a briefing to the team regarding

this program. We also had discussions with David Rhodes, the MHDL Army Program Manager, about how the two efforts might be coordinated. Our goal was to achieve synergism and avoid redundancy, to avoid re-defining anything of value from one effort, within the other.

"European" 1076.1 Working Group (WG): We reviewed the on-going work of the WG. At this juncture, the WG enjoyed strong European participation. Its organization was as follows:

Chair:	Jean-Michele Berge (French Telecomm)
Language Design Chair:	Alain Vachoux (EPFL - Swiss Federal Institute)
Validation Chair:	Joerg-Oliver Fischer-Binder (Bosch)

Team members Stan Krolikoski, Mark Brown and Ernst Christen attended the WG meeting at EuroDAC. There was some concern expressed by the Europeans that the U.S. DoD was trying to "take control" of the VHDL-AMS (1076.1) process. The concerns by the Europeans were due to a coincidence of two effects: the award of the Rome Lab funding, and the foundation of AVI. This started during EuroDAC and culminated at the meeting in October 1993 (p.13). What made it even more suspect to some people was that in both cases Stan Krolokoski and Ernst Christen were involved very heavily. Our position was that we were all contributing to the language definition effort within the open IEEE process. Due to the efforts of these team members, the Europeans' concerns were, for the most part, put to rest, and the entire standardization process was able to continue in a cooperative manner.

Language Extension Specification (LES) Organization: At this time, the 1076.1 WG had produced a preliminary Design Objectives Document (DOD). In general, in order to manage the language development process, they had organized their efforts around functional topics, which were named "Language Extension Specifications (LESs)" These LESs were the mechanisms for defining and reviewing the analog and mixed-signal extensions. They consisted of the following:

LES-A:	Analog Types
LES-B:	Quantities
LES-C:	Operators and Attributes
LES-D:	Controlled Signals (Coupling), Import/Export of Quantities
LES-E:	Sequential Assignment

LES-F: Natures
LES-G: Nodes
LES-H: Pins, Import/Export of Nodes
LES-I: Frequency Analysis
LES-J: Contribution Statement
LES-K: Equation Set Statement
LES-L: Interpretation Domain
LES-LL: Analog Subprograms
LES-M: Analog Events, A/D Interaction
LES-N: Simulation Cycle
LES-O: Analog Units, Physical Types
LES-OO: Dimensional Analysis
LES-P: Mathematical Package
LES-Q: Electrical Package
LES-R: Tool Interaction, Simulation Control
LES-S: Other Execution Control Packages
LES-T: Mixed Net-Lists (Pins & Ports), Conversion Model

Requirements and Rationale Documents: Work on these items had already been started by the "European" 1076.1 WG. The AHDL team reviewed the material which had been produced to date, and determined how the AHDL program versions of these documents should be produced.

Validation Effort: We determined that this work was to be coordinated with the 1076.1 Validation Chair (Joerg-Oliver Fischer-Binder) and with AVI. We left the issue of how actively they wished to participate in the definition or execution of any validations to the discretion of the WG Chair.

In ***summary of this period's activities***, we started the AHDL contract, and began interaction with the 1076.1 WG. Here, we gained an understanding of their work to date and the processes and procedures they had in place. We also became aware of the potential difficulties that lay ahead, due to the need to coordinate with an organization with disparate, international participation.

OCTOBER-DECEMBER 1993

Activities in this time period involved both technical and coordination aspects. In the technical realm, the AHDL Team reviewed existing 1076.1-developed material, addressed a critical issue regarding simulation cycle management, and considered the need for an additional construct and suggestions regarding validation from other 1076.1 WG members. Regarding coordination, we mitigated potential European-USA conflicts,

and assisted with 1076.1 WG organizational and coordination issues. Also, the MTL program management responsibilities changed. We elaborate upon these below.

Existing DOD Review: In November, Mr. Peter Liebmann of Compass Design Automation joined the AHDL team as Mark Brown's replacement. He performed a comprehensive analysis review of the Design Objectives Document (DOD), and provided suggestions for changes.

Language Design: Ernst Christen continued his efforts regarding simulation, and presented information about the VHDL-AMS Simulation Cycle (LES-N) to the AHDL team and to the WG.

Validation: We made presentations to both AVI and to the 1076.1 WG concerning pertinent validation issues, including language, tool, and library validation. At this juncture, the 1076.1 Validation Committee Chair had established no specific criteria for validation, but we needed to make some progress in this area. We decided, in concert with both AVI and the 1076.1 WG, that the WG would concentrate on language validation and that AVI would concentrate on tool and library validation. Based upon this definition, the AHDL team was able to confront validation issues and coordinate with the appropriate organization.

Bouncing Ball Example: Eduard Moser of Bosch presented a model that simulates the dynamics of a bouncing ball. We mention this particular potential validation model because it brought up issues which had not been discussed in the language design work so far. These issues, the most significant of which was discontinuities, revealed the potential need for an additional language construct to deal with them.

Cadence Design Systems, Inc. (Cadence) critique: Ken Kundert and Dan Fitzpatrick from Cadence offered their critique of the 1076.1 effort. They initially wanted to submit their suggestions to AVI to be formulated as requirements to the 1076.1 WG. However, AVI rejected the idea, since the standards development process within the IEEE requires that committees be made up of individuals, not companies or organizations. Ernst Christen suggested that a U.S. design team, lead by MTL/Analogy/Compass, could include Cadence. Ken and Dan expressed interest to actively participate.

1076.1 Working Group (WG): AHDL team members attended a WG meeting on October 15, 1993 in San Jose. The WG operated under the IEEE Design Automation Standards Committee (DASC). The DASC

had changed into a membership organization requiring each WG to have an executive committee and had established rules for voting. To provide for a truly international WG, it was decided that the chair or vice-chair should come from the U.S. and the other from Europe. Presentations: Kim Hailey (MetaSoft) spoke about library issues. Dan Fitzpatrick (Cadence) critiqued the WG work and suggested that the group reopen the language requirements. This generated much controversy, especially among the Europeans.

European Team Concern: The Europeans continued to foster (and voice) concern over the respective roles of our team, AVI, and where they fit in the development and standardization process. The AHDL Team (MTL/Analogy/Compass) again asserted that we all needed to work together to realize an effective language development and standardization process. To address the concerns due to RL funding and AVI, several presentations were given. Stan Krolikoski talked about AVI's goals, Kim Hailey about how AVI perceived library issues, and Ernst Christen walked the line on validation, proposing how to separate language validation (to be done by the WG) and tool validation (planned by AVI). Although there was no special presentation on how the AHDL effort would help the WG effort, extensive discussions were held with some Europeans who believed they were being "outmaneuvered." We proposed to work with them using the existing language design organization, and we did that until June 1994, when Ernst Christen proposed the formation of the Tiger Team, because we had made virtually no progress in eight months using the previous approach. The major stumbling block preventing progress was the fact that each of the functional topics was built from the bottom up. The WG was then having difficulty meshing the topics at the higher levels.

New 1076.1 Working Group (WG) Organization: The 1076.1 Executive Committee was reorganized along the suggested paradigm of joint European-USA Chairs. As such, the ***Executive Committee*** was established as follows:

Chair:	Jean-Michele Berge (French Telecomm)
Vice-Chair:	Ernst Christen (Analogy)
Secretary:	Alain Vachoux (EPFL - Swiss Federal Institute)

The following ***Subcommittees*** were also defined:

Requirements Chair:	Dan Fitzpatrick (Cadence)
Requirement Vice-Chair:	Hazem El Tahawi (AnaCAD)
Language Design Co-Chair:	Jean-Michele Berge (French Telecomm)
Language Design Co-Chair:	Alain Vachoux (EPFL - Swiss Federal Institute)
Language Design Vice-Chair:	Ernst Christen (Analogy)
Validation Chair:	Joerg-Oliver Fischer-Binder (Bosch)
Validation Vice-Chair:	vacant
Documentation Chair:	David Smith (Analogy)
Documentation Vice-Chair:	Kevin Walsh (AnaCAD)

AHDL Program Review: The Program Review Meeting was held on November 10, 1993 at San Jose. Here, we presented our progress to date on all contractual efforts.

Funding: At this point in the program, and the standardization process at large, there were two significant funding sources for the VHDL-AMS development and standardization, outside the normal, "donated" participation of individuals and interested organizations. The European funding was through ESPRIT, to the team headed by Jean-Michele Berge and Alain Vachoux. The U.S. funding was, of course, through the subject USAF Rome Laboratory AHDL contract to the MTL Systems/Analogy/Compass Design Automation team.

Projected Schedule: At this point in time, the 1076.1 WG had scheduled the language design and validation to be completed, with a LRM, by Fall 1994, and expected balloting in late 1994 to early 1995. This was not necessarily compatible with the AHDL contractual schedule, and it was a point of concern.

Mail Reflectors: To facilitate 1076.1 WG member communications and data exchange, Internet E-Mail reflectors were placed on-line in December, 1994, to support the VHDL-AMS effort. The address was (and still is) 1076-1@epfl.ch.

PM Change: In December, Wenying Zhou became the AHDL program manager. Wenying brought a more technically-oriented flavor to the position, which MTL believed would facilitate interactions with Rome Laboratory, the 1076.1 WG, and our subcontractors alike.

In ***summary of this period's activities***, we confronted certain technical and coordination aspects, again needed to allay European concerns, attended a WG meeting, conducted a program review, and changed program managers. The *inability to control the 1076.1 schedule*, coupled with the *need to produce certain deliverables for the USAF according to the contract schedule* was revealed to be a problem which would not be readily resolved throughout the effort.

JANUARY-MARCH 1994

In this period, we addressed the (MMIC HDL) MHDL-VHDL-AMS synergism issue, and continued reviewing LESs and addressing constructs issues. We also attended 1076.1 WG meetings and continued our coördination with the WG. Also, the language design and LRM writing began in earnest, and a commercial analog HDL was investigated. The LRM work during this period was more organizational in nature, than documenting language changes. Specifically, we explored various ways of annotating the 1076 LRM, and we produced something like an "impact analysis", i.e., a list of what parts of the LRM are impacted by VHDL-AMS, and where each piece of VHDL-AMS would be most likely documented. We now elaborate upon these events and activities.

New Analogy technical participant: In January, C.-J. 'Richard' Shi of Analogy joined the AHDL team. He was hired by Analogy specifically to work on this contract. Richard provided the technical support necessary to permit Ernst Christen to attend to both technical and 1076.1 coordination aspects.

MHDL Interaction: AHDL Team members attended the MHDL Conference in Tempe, AZ on January 26, 1994, which was co-located with a 1076.1 WG meeting. We learned that the language design was in 'good shape' but there was no implementation. We wrote an analysis of the MHDL design in the context of determining what portions of the language design could apply to VHDL-AMS. In particular we noted that MHDL is oriented toward layout description of components with emphasis on design rule specification and checking. This was in contrast to the primarily behavioral modeling character of VHDL-AMS.

1076.1 WG Meeting: This meeting, which was co-located with the MHDL Conference and IEEE SCC-30 group in Tempe, AZ, was held on January 27-28, 1994. In addition to committee reports, Hal Carter of the University of Cincinnati (UC) presented an overview of AnaVHDL, a minimalist approach to an analog-extended VHDL developed under UC's DARPA-sponsored QUEST Project.

Technical Activities: We performed reviews of the A/D Interaction (LES-M) and the Bouncing Ball problem. Peter Liebmann, Stan Krolikoski and Erich Marschner wrote an analysis of, and proposal for, revisions to the 1076.1 LESs.

LRM Writing: The first LRM Committee Meeting was held on January 26, 1994. The Committee decided that the writing should not be a separate effort but primarily a compilation of the LES work. The issue of what form the document should assume (should it *reference* the VHDL standard (1076) or *include* 1076?) was discussed without resolution. Authors were assigned to be Peter Liebmann and Erich Marschner. They, along with Ed Cheng, the current Validation Vice-Chair, and Kevin Walsh, had reviewed the LESs, and determined where the extensions would fit into the VHDL LRM. They had found no major problems at that time.

Language Design: A view of one of the major stumbling blocks was coming into focus at this point in time. The basic problem was whether VHDL-AMS should *extend VHDL constructs and semantics or define its own.* This issue remained active throughout the entire process: when to define new constructs *versus* when to overload. We now summarize these views and the subsequent resolution.

The separation view: The original VHDL-AMS developers (Europeans, thru LESs) believed that analog components are so different from digital components that the language design must clearly distinguish the two. For example, digital signals (such as fixed-level voltages representing logical 1s and 0s) are discrete and event driven, while analog signals (such as dynamically-variable voltages) are continuous and solutions to non-linear differential equations.

The extension view: The other view was that present constructs in VHDL could be extended to mean different things. "Signals", which are already overloaded to describe files, could be used to describe the structure of analog signals much the same way they do for digital signals.

Resolution: A vote was taken and evaluated to define which direction the language design should take. The most significant issue was whether analog signals and the equations describing them should be separate from digital signal descriptions. The idea of separating analog "pins" from digital "ports" was accepted. Also, new blocks of "procedurals" and equation sets were accepted. The vote was basically that the LESs should be accepted almost as

is. Although containing elements of both points of view, the definition was clearly biased toward the extension point of view. This was considered to be beneficial for rapid VHDL-AMS design tool development, since adaptation of VHDL-based tools would be easier and more likely than in the case of a language containing largely different (from VHDL) constructs or semantics.

AnaCADs HDL-A Product: It was a foregone conclusion that there would be some level of analog-HDL product development which would proceed concurrently with, and not necessarily in consideration of, the standardization process. EDA tool developers are highly competitive and anxious to beat the competition to market, and their product development demands will not necessarily await a standardization process. Our hope was, of course, that those developments would await the standard or at least consider it in their development. An early instance of such a development that we investigated was AnaCADs version of VHDL-AMS which they were shipping as a product in this period. Aside from a few semantical issues, it appeared to follow the LES documents quite closely, which was encouraging and considered positive for the standardization process.

In ***summary of this period's activities***, all aspects of the program were flowing smoothly. Coordination with the 1076.1 WG was becoming easier, all participants were accepting the duality of European and U.S.-sponsored support, and collectively, we were focusing principally upon the technical challenges.

APRIL-JUNE 1994

In this period, we attended a conference where we were able to promote our efforts through some panel discussions, continued the language development and LRM work, changed program managers, and closed out the MHDL interactions. The AHDL Team made a significant contribution to the effort by suggesting the formation of a small, focused "Tiger Team" to resolve all open issues. This Tiger Team evolved later into the Language Architecture Team, which ultimately streamlined the standardization process and enabled the LRM development to proceed vigorously. We now describe these activities and events.

Technical Conference: At the Spring VHDL International Users' Forum (VIUF) we participated in a panel presentation on Analog HDLs. Ernst Christen presented for the 1076.1 Working Group, Stan Krolikoski presented for AVI, and David Barton presented for the MHDL Group. Wenying Zhou of MTL was the panel moderator. There were 150 attendees and the presentations were well received.

PM Change: In June, Joe Mitchell of MTL was named the new MTL AHDL program manager. Wenying had departed to work in design automation product development. Although we regretted the loss of Wenying's technical abilities to support the program, the AHDL program seemed to be evolving into more of a management than a technical effort on MTL's part, which was its original concept. Joe brought organizational and disciplined program management capability to the effort.

Language Design: We started active discussions with IC designers and model developers about language constructs. We also worked to clarify poorly defined issues in the LESs, specifically: analog types, entity overloading, natures and nodes, equation sets and A/D-D/A interaction. At the 1076.1 WG meeting Ernst Christen proposed to form a small, focused "Tiger Team" to resolve all open issues. This proposal was accepted by the WG, and the team was staffed with representatives from Analogy, AnaCAD, Compass, CNET, and ESIN. The first meeting was scheduled to be in Grenoble, France, on July 10-15, 1994.

LRM Writing: We were writing the LRM chapters based on the LESs, with the intent to send the written chapters to the language design group for comment. In the course of this activity, we found that a number of aspects were incompletely defined and would require more work by the language design group. Specifically, we needed definitions of *through and across* quantities, and multiple drivers of analog quantities. At this point, we had written an outline of the LRM and chapters 1, 3, 4 and 5, and sent them to the Language Design Group (Sub-Committee) for review. Our goal at this point was to have an acceptable LRM out to ballot by the end of January, 1995.

Validation: We collected a group of seven benchmarks, which were called the "EuroSim benchmarks." They included particle physics problems, electrical problems, control system problems, and queuing problems. Such an assimilation of electronic, physical, and process models were viewed to be a good set for our validation purposes.

MHDL Interaction: We finished analyzing the MHDL documents and decided that the language was different enough from VHDL-AMS that a detailed analysis would not contribute to the VHDL-AMS effort. While we agreed to maintain liaison with this program, further, rigorous assessments of compatibility or synergism were deemed unproductive. Our final assessment of the AHDL-VHDL-AMS interaction was to be articulated in a high-level analysis.

In ***summary of this period's activities***, we were not pleased to once again change PMs, but saw this as unpreventable due to the circumstances. While the language development and LRM work was progressing technically, the 1076.1 schedule for LRM delivery was again slipping, which reinforced our concerns over meeting contractual schedules.

JULY-SEPTEMBER 1994

In this period, we welcomed a new participant from Compass, continued language development and LRM activities, confronted concerns from a WG member, and finalized our conclusions regarding MHDL/VHDL-AMS relationships. In this period, the LAT began to display its capability to resolve matters and move forward aggressively, to the ultimate benefit of the standardization process. We now elaborate upon these topics.

New Compass Technical Participant: In August, Mr. Kenneth Bakalar of Compass Design Automation started working with the AHDL team. As an expert in VHDL, he worked to develop a description of the language extensions in terms of the VHDL 1993 LRM. Ken's participation in the program significantly enhanced our ability to support language design needs, and was key to moving this process along as rapidly as was possible, given the constraints of the 1076.1 scheduling.

Language Design: The Tiger Team of language design experts (renamed the 'Language Architecture Team' (LAT)) from both Europe and the USA met for the first time as previously scheduled, and twice more:

- In Grenoble, France from July 11 to15, 1994 (LAT meeting #1),
- In Columbia, Maryland from August 29 to-September 1, 1994 (LAT #2), and
- In Grenoble again from September 23 to 27, 1994 (LAT #3).

The LAT met to resolve open issues and push the VHDL-AMS effort to completion as soon as possible. Taking a "top-down" approach, the group was to help revise the Design Objectives Document (DOD), the Design Objectives Rationale (DOR) and many of the LESs. A new, consistent, VHDL-AMS specification would allow for writing an acceptable LRM. The LAT wanted to complete the language design itself but Dan Fitzpatrick of Cadence questioned this approach. While at the LAT meeting, we found the main issue was that different people had different interpretations of the meaning of the syntax presented in the LESs. Hence, there was

a certain level of clarification to accomplish before the real work of the LAT could begin, which essentially consumed the first meeting.

Cadence Issues: Dan Fitzpatrick of Cadence stated that the Working Group had not addressed all the concerns raised by Cadence concerning requirements, language architecture, and language design. Cadence's position was that they would begin work on their own analog extensions to VHDL. We believed that we had responded properly to their concerns, and that their suggestions were considered in our work. Several ideas had a positive impact on our work and some were rejected after long discussions. We really had no control of, and precious little influence upon, what some independent organization such as Cadence chose to do. In our opinion, we were conducting a development and standardization process in as responsive and professional a manner that we could.

LRM Writing: The LRM team met in San Diego to coordinate the LRM effort with the language design effort. Compass proposed that the LRM team should be a part of the Tiger Team and have a separate series of intense, week-long meetings to finalize the writing. They recommended that the group be kept small (at most 5 people) and that they keep the rest of the Working Group apprised via email. The target date for the LRM was moved back six months to July 1995.

MHDL Relationship: We completed our high-level analysis of the relationship between VHDL-AMS and MHDL. The following summarizes the important differences:

1. Not all MHDL descriptions are simulatable, and VHDL-AMS is *simulation-oriented.*
2. MHDL can handle distributed elements, while VHDL-AMS, as an extension to VHDL, deals only with lumped elements.
3. MHDL can describe layout geometries, which are of course significant to microwave frequencies, while VHDL-AMS cannot.
4. MHDL uses explixit equations while VHDL-AMS uses a combination of explicit and implicit equations.

Here, we see that a principal reason for the lack of good MHDL/VHDL-AMS synergism is a consequence of MHDL's high-frequency handling nature, and the WG's decision, earlier, to implement VHDL-AMS as an extension to VHDL. Had VHDL-

AMS followed the course of different constructs and semantics, there may have been more opportunity for synergism. However, even in this case the high-frequency nuances of MHDL would have been of little value to, and perhaps a complication to, VHDL-AMS. Although it may have precluded any MHDL/VHDL-AMS sharing or compatibility, we believe the extension approach is still the correct one, for the reasons we discussed earlier.

In ***summary of this period's activities***, Ken Bakalar, our new participant from Compass, proved to be a decided asset to the language development and LRM activities. Also, the concerns from a WG member were addressed satisfactorily. Finally, our conclusions regarding MHDL/VHDL-AMS relationships confirmed the WG's selection of an *extension* (of VHDL) posture for VHDL-AMS to be a proper one.

OCTOBER-DECEMBER 1994

In this period, we continued the language design activities, principally through white paper submittal, and addressed some validation issues. Here, we fully realized the value of the LAT-coordinated white paper paradigm for developing and considering language extensions. These activities are described below.

Language Design: Ken Bakalar (Compass) wrote a 'white paper' on quantities, nodes, and terminals. We had decided to continue this process by writing a series of working white papers that stress semantics rather than syntax. The white papers were to be written in the LRM style. They would be presented to the LAT first and then, once agreement is reached, to the Working Group as a whole.

We attended the Language Architecture Team meeting in Columbia, Maryland, which was held concurrently with a WG meeting in Tysons Corner during the same week, from November 16 to 19, 1994 (This was LAT #4, scheduled due to necessity following LAT#3).

The need for this activity was because the LESs were originally developed from the bottom, or detailed level, and then needed to be meshed together at the top level. However, the number of inconsistencies among the bottom-up-developed LESs prevented this meshing. Hence, the design philosophy was switched to a top-down approach, where the concepts would be defined in technical white papers, and then embellished with the prior LES work as much as possible.

At the meeting Ken Bakalar's Quantities, Terminals and Nodes white paper was adopted by the LAT. Meanwhile, Ernst Christen was writing white papers on equation formulation (number of equations), initialization, and DC operating points. Other white papers in process at this time were: (1) Mixed-Mode Simulation & Analog Events (simulation cycle, break ability, and implicit analog events), (2) Physical Systems, (3) SPICE-VHDL-AMS Compatibility, (4) Mixed A/D Simulation Cycle, and (5) Analog (continuous) Time.

Validation: We developed three validation examples: (1) a PLL (conservative semantic), (2) a motor controller (signal flow semantic) and (3) a D/A converter. These models used the tentative syntax which had many problems including inconsistencies and missing pieces. It was our assessment that the Validation Committee was not prepared to provide forceful or assertive guidance for validation, and that such activity would need to progress on a *de-facto* basis if it was going to progress at all.

In ***summary of this period's activities***, the white paper paradigm appeared to be a good one for getting material into the 1076.1 process, and the development activity continued to make progress from a technical perspective. Validation issues did not appear to be gaining serious attention within the WG, which was a potential concern for later activities.

JANUARY-MARCH 1995

In this period we suffered another PM change, and continued the language design and validation efforts. The LAT meetings were making technical concept review more efficient, and the entire technical effort was proceeding unimpeded. Hence, we were comfortable, if not altogether overjoyed, at the need to change our program manager once more.

PM Change: In February, Ken Simone of MTL was named the new AHDL program manager. Although we realized that yet another PM change was inconsistent with good management practice, Joe's abrupt departure left us no choice. Ken was an astute and seasoned professional in the electronic design automation world, and we had confidence that he would continue to manage the program effectively.

Language Design: The LAT meetings continued, now well beyond the originally-conceived first three. However, the LAT was becoming the mechanism for rapid evaluation of white paper concepts and

incorporation of selected ones into the design. Hence, they were providing a necessary expediting service to the WG. The Language Architecture Team had a meeting in Lausanne, Switzerland from January 31 to February 3, 1995 (LAT #5). The LAT members had all 7 white papers to review at the meeting. The Quantities and Mixed-Mode Simulation Cycle white papers were provisionally adopted by the LAT.

Language Architecture Document: Ernst Christen wrote an informative overview of the VHDL-AMS language architecture as the first release of the Language Architecture Document. This was not an AHDL program deliverable, but a necessary component of the language design. It would also ultimately become part of the review package for balloting.

Validation: The AHDL Team reviewed several examples developed by Ken Bakalar. We converted some examples to Analogy's MAST language in order to identify whether the descriptions were complete and simulatable.

In ***summary of this period's activities***, our PM change was made with little impact, and the technical effort, having substantial momentum of its own and being assisted by the LAT meetings, continued to make progress.

APRIL-JUNE 1995

In this period, we continued the language design process, evaluating suggestions made previously, and reviewing several white papers, in the course of two LAT meetings and a program review. We summarize these activities below.

Language Design: The Language Architecture Team held a meeting in San Diego, California, from April 4 to April 7, 1995 (LAT #6) at the Spring VIUF Conference. The LAT members had 12 of 14 white papers to review, 6 were discussed, 3 were provisionally approved. We identified another 5 white paper topics and assigned them to various authors among the AHDL Team and WG.

New Participants and challenges: In April the following changes occurred in the WG organization:

- Jean-Michel Berge resigned as co-chair of the Language Design Committee and was replaced by Ken Bakalar, who was elected by the WG.

- Ernst Christen, who was an LDC vice-chair, also became a co-chair.
- Dan Damon was elected by the WG to replace Ed Cheng as Validation vice-chair.

An emerging problem within the WG, which is typically a major problem inherent within an open working group, was a function of new participants who lacked the historical perspective on VHDL-AMS. Many of the newcomers to the working group were unconvinced about the direction of the language design, not having been through the process but only seeing the current activities.

Differing opinions: Another major problem continued to be individual interests based upon individual corporate philosophies and interests, coupled with better perspective gained from the more complete definition. For example, Cadence wanted an almost purely procedural language, and they provided a description of their alternative. Similarly, AnaCAD felt that the present language definition was inferior to the incomplete model described in the LESs. While such problems had to be dealt with, the VHDL-AMS language, in whatever form would finally be accepted, could not be perfect for everyone.

White papers: New white papers included the topics of (1) Solvability of DAEs (differential algebraic equations) and (2) Statistical Modeling.

Consolidation: The Working Group agreed to consolidate the Language Architecture Team (LAT) and the Language Design Committee (LDC) into one. The LAT had been working very effectively to expedite the process to this point, and our hope was that this consolidation would not encumber the LAT's demonstrated efficiency.

Another LAT meeting: There was another Language Architecture meeting in San Francisco, CA from June 12 to June 16, 1995 (LAT #7) during DAC. Here, we discussed AnaCADs review of the LDC work and two alternative proposals for branches. We also provisionally approved the white paper on analog time.

Evaluation of Cadence suggestions: Ernst Christen and Ken Bakalar analyzed the probe/source model (as opposed to branches) proposed by Cadence. They derived and documented the semantics based on Cadence's syntactic descriptions. We believed there was value in understanding the approach to define a better overall language.

We concluded that, subject to some modifications, the probe/source approach was as powerful as the branch-based mechanism described in the white papers, but the Cadence representatives did not accept any modifications and failed to provide a coherent and unambiguous definition of their approach. We finally rejected the probe/source model for this reason and because the underlying paradigm of controlled sources, albeit familiar to SPICE users, was foreign to people with no such background.

Program Review: We held a Program Review Meeting at Rome Laboratory on May 2, 1995. The presenters were Ken Simone, Ernst Christen and Ken Bakalar.

In ***summary of this period's activities***, progress continued on the language design, with critics' concerns being considered and white papers being reviewed for incorporation into the language.

JULY-SEPTEMBER 1995

PM Change: In August, Bob Collins of MTL was named the new AHDL program manager. Again, we realized that yet another PM change was inconsistent with good management practice, but by this time we were becoming accustomed to it. With similar qualifications to those of Ken Simone, the departing PM, Bob was a seasoned professional in the electronic design automation world, and with the majority of the effort behind us, could easily guide the program to its conclusion.

Language Design: In this period, Cadence was continuing to push very strongly to have their solution adopted in whole, claiming it was the only acceptable choice. We expected that this issue would have to be resolved by the WG at large and the subsequent balloting process.

At the Language Design Committee (LDC) meeting in September 1995 in Brighton, UK, we discussed several topics for the first time: Mixed Netlists, Tolerances, Frequency Domain Support and Dimensional Analysis. The unanimous decision was to not support dimensional analysis at this time, as it required changes to the VHDL type system. Only 4 weeks later, at the meeting in Boston, MA, it became clear that both Anacad and Cadence were not willing to accept the language design work that they had agreed to earlier. It became difficult to get consensus on issues, and progress was becoming very slow.

At that time, the Chairman of the 1076.1 Working Group, Jean-Michel Berge', stepped in and proposed a resolution process that would involve the voting members of the 1076.1 Working Group. Anybody interested had time, until January 15, 1996, to submit as complete as possible a proposal in that time frame. After that deadline, the submitted material would be made available to the WG members and to three VHDL experts, who would make a recommendation to the WG. Finally, the voting members of the WG would select a single proposal by simple majority. Only the selected proposal would be brought to completion. All LDC meeting attendees agreed to this process, and they committed to support the selected proposal.

Contract Completion: At this point, the contract was approaching its conclusion, and our efforts turned toward producing the final contract deliverables (this report and the USAF deliverable LRM).

OCTOBER, 1995 - CONCLUSION

Language Design: By January 15, 1996, two proposals were submitted. They were code-named *Opal and Jade*, Opal being the language developed by the LDC with funding from Rome Lab, and Jade being a Mentor/Anacad proposal.

At a 1076.1 Working Group meeting at the end of February, 1996, both proposals were presented by their primary authors, and the VHDL experts presented the result of their review, together with the recommendation that "Opal is the better fit for VHDL." During the four week voting period, strengths and weaknesses of the two proposals were discussed by email, and many questions from voters were answered. At the end, the Opal proposal was selected by the WG with 38 votes over 11 votes for Jade, with 2 abstentions. Language design work based on the selected Opal proposal is now approaching completion, and, as previously agreed, the result is supported by all participants.

Final Documentation: In this period, the technical effort concluded and the activities necessary to produce and deliver the final documentation (LRM and Final Report) were conducted. The language development effort continued with private funding. As the LRM did not come to fruition during the contract period, and because of copyright and other legal issues with the IEEE, a change of deliverable was needed to fulfill the LRM requirement. The decision was made to

substitute the white papers, a large portion of which were developed due to this effort's funding, in place of a balloted LRM.

In ***summary of this chronology***, we have described the events and interactions which occurred throughout the duration of this effort, and described the activities of the AHDL Team which supported and facilitated the process. Next, we summarize the language development process as a whole, in the context of lessons learned and how well we achieved our goals and objectives.

2.3 Summary of the Language Development Process

In the previous section, we presented a chronology of significant events over the duration of the subject contract. This, however, does not tell the whole story. These events were embedded within a language development process which:

a. Was administered under the standardization process of the IEEE
b. Was supported by the subject Rome Laboratory AHDL Contract
c. Included the participation of an international array of governments and commercial interests.

In other words, many diverse organizations were active in the language development and standardization processes, yet not under the explicit control of any one entity or organization. Although the WG was, by definition, the explicit control point, this was not effective in practice. While the WG Chair attempted to exercise diplomacy, basically requiring a concensus on issues, the individual members often followed their parochial interests very stubbornly, thus precluding such concensus. Furthermore, the membership represented more of a vendor's perspective than a user's view. Hence, it is incumbent upon us, in this report, to document how we attempted to manage the AHDL contract such that it served its purpose to enhance and support the language development and standardization processes, in the face of such diversity. In this section, we attend to these issues with a discussion of the project management approach (Section 2.3.1), and the degree of success we achieved in accomplishing the program goals (Section 2.3.2).

2.3.1 Management Approach and Challenges

Our initial concept of this program, as we have mentioned throughout this report, was to facilitate the language development and standardization process. That is, we sought to provide the technical support to permit the 1076.1 WG to execute its function more efficiently. However, as Figure 2.3.1-1 indicates, the 1076.1 WG had multiple connections to multiple "supporters." Furthermore, these outside entities were also "connected" to the AHDL Team via paths other than through the WG. Hence, some challenges arose for our management paradigm. Next, we address several of the

challenges we encountered in a summary fashion, drawing upon the more specific discussions of the chronology presented earlier, in Section 2.2

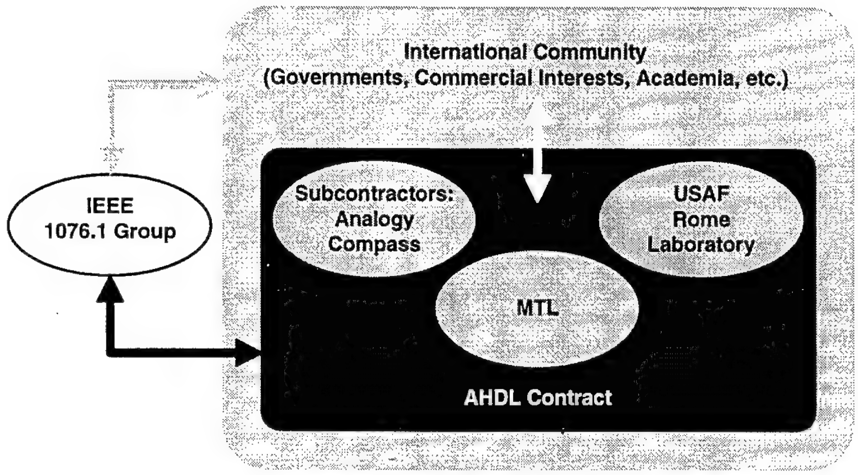

Figure 2.3.1-1: 1076.1 WG Support from Various Organizations

Challenge 1 - Getting started: Our management paradigm assumed a more-or-less usual spinup process, involving placing Analogy and Compass under contract, setting schedules and milestones, activating tasks and executing the effort. This, we discovered, was not possible, principally due to the need to coordinate with the IEEE. In particular, the need to allay the concerns of certain factions within the WG, that U.S. Government sponsorship was an attempt to exert inordinate control over the standardization process, consumed valuable resources at the beginning of the program.

Solution: Ultimately, we overcame this challenge through the vigorous efforts of our team members, and simply by our actions. Once we demonstrated that our motivation was indeed to support the standardization process and not to control it, the cooperation necessary to work effectively with the WG was accomplished, although a lingering uneasiness persisted.

Challenge 2 - Maintaining Technical Focus: We recognized this aspect as a challenge right from the beginning, but had the wrong perspective upon it. Going into the program, in fact even in the early stages of conceiving the approach we would propose, we recognized that success depended upon proper technical focus. That is, we sought to isolate the technical personnel from the administrative and organizational aspects, to permit them to focus upon the technical needs of language development and standardization. Recognizing that our two principally-technical subcontractors, Analogy and Compass, lacked MTL's experience in government contracting, we

postured MTL as a liaison between Rome Laboratory and these subcontractors, as we depict in Figure 2.3.1-2. Our assumption was that by buffering them from the Government contracting nuances, we would permit them to focus intently upon the technical effort. We also assumed that they could coordinate effectively, on a technical basis, with the 1076.1 WG more or less unassisted.

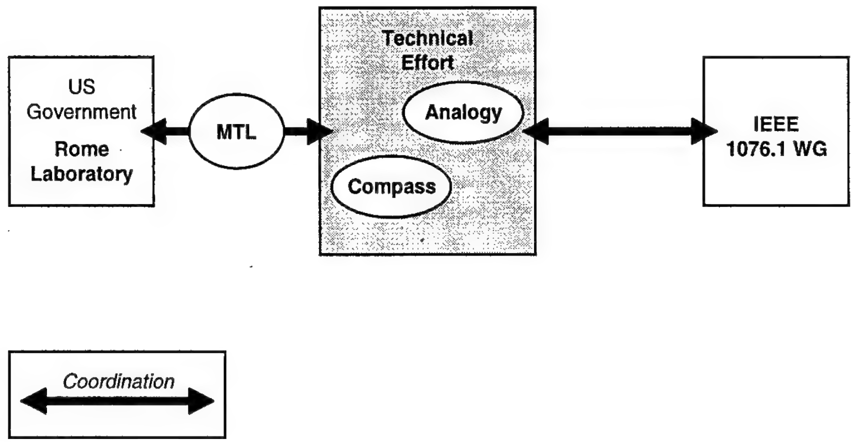

Figure 2.3.1-2: MTL as Coordination Buffer to Rome Laboratory

This was an erroneous assumption. As it turned out, coordination with Rome Laboratory, in both contractual and technical aspects, was not the issue. The challenge, instead, turned out to be coordination with the 1076.1 WG. The procedural aspects of such coordination, coupled with the international perspective, parochial interests of certain factions, and a continuing uneasiness over U.S. government sponsorship, although lessened from what it was at the beginning, became detractors to the technical effort. MTL at first attempted to assume a buffering role to mitigate this problem, as illustrated in Figure 2.3.1-3, but was not effective. Our subcontractors had the skills and knowledge to interact with the IEEE, but their doing so took precious time and resources away from the technical effort. MTL had some time and resources, but these were stretched very thin to handle both the Government and IEEE coordination. Besides, MTL really lacked the background and skills to effectively provide the IEEE coordination.

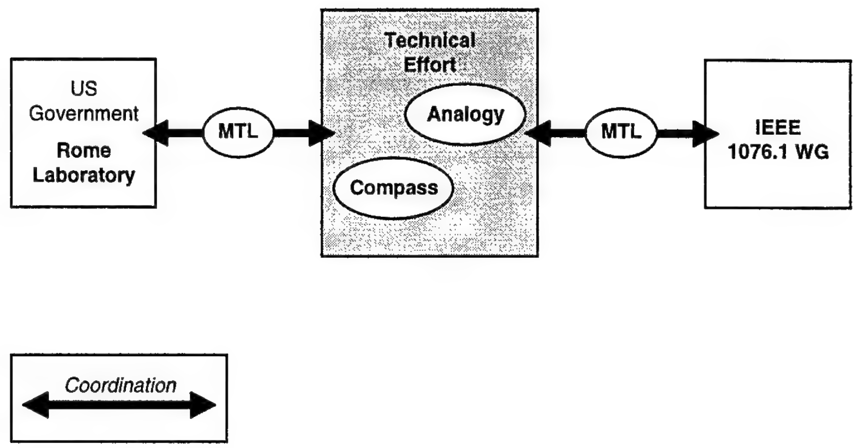

Figure 2.3.1-3: MTL Attempting to be a Coordination Buffer for Rome Laboratory and the IEEE

Solution: The solution to this challenge was provided by the Language Architecture Team (LAT). This team included AHDL Team personnel as well as other WG participants. Using this level of manpower, their effect upon the whole process was to allow the AHDL Team's technical subcontractors, as well as other technical WG participants for that matter, to submit technical concepts as white papers. The LAT then managed the process of inserting these concepts into the WG procedures. It worked very well, and permitted MTL to resume the posture of Government liaison, as depicted in Figure 2.3.1-4. The entire process worked quite smoothly after the LAT assumed this role.

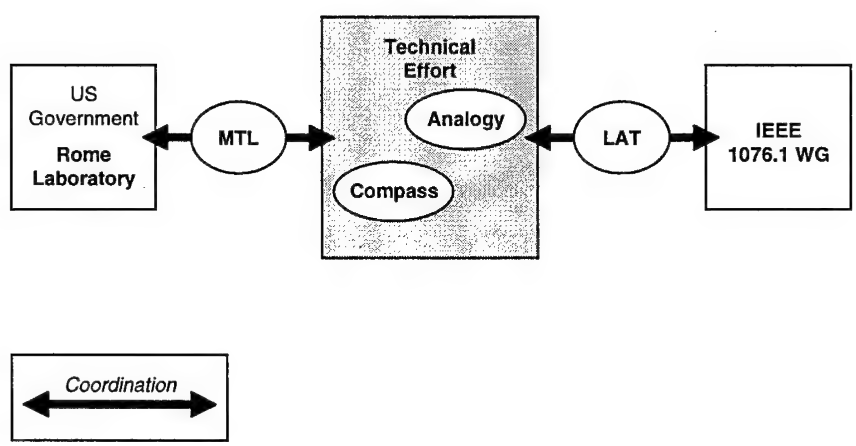

Figure 2.3.1-4: MTL and the LAT in Their Respective Coordination Roles

Challenge 3 - Meeting Schedules: The challenge in meeting deliverable schedules was a function of two factors: (1) the inability to control or predict the 1076.1 WG schedule, and (2) the differing needs of the IEEE documentation and the contractually-specified documentation. We address the first aspect here, and leave the second one to the discussions under Challenge 4 - Producing Deliverables.

The fundamental problem was that the IEEE is an independent organization, not under the control of any contributing entity. Within the 1076.1 WG, they set schedules for certain elements of a language development, and when they see that some deadline will not be met, they simply re-schedule it. This is perfectly reasonable and satisfactory for an organization which is under no pressure to meet deliverable deadlines, and is not investing their own funding or resources in producing the deliverables. Since the majority of the labor required to produce a standard is contributed, the IEEE is perfectly content to work in this fashion.

The AHDL contract, in contrast, is a government-funded mechanism by which the Government expects to receive particular results of specified format and expected quality, according to a defined schedule. Specifically, disregarding the routine reporting requirements, the deliverables to be produced under this effort included:

CDRL-A004 A Language Requirements Document,
CDRL-A005 A Language Rationale Document,
CDRL-A006 A Language Reference Manual, and
CDRL-A007 A Final Report (this document)

The first three of these items required material produced not only by the AHDL Team, but also by other members of the 1076.1 WG. Hence, we found ourselves in the situation depicted in Figure 2.3.1-5, requiring material from an entity which was not part of the contracted effort. Outside the obvious scheduling and control problem, this situation also raised copyright issues.

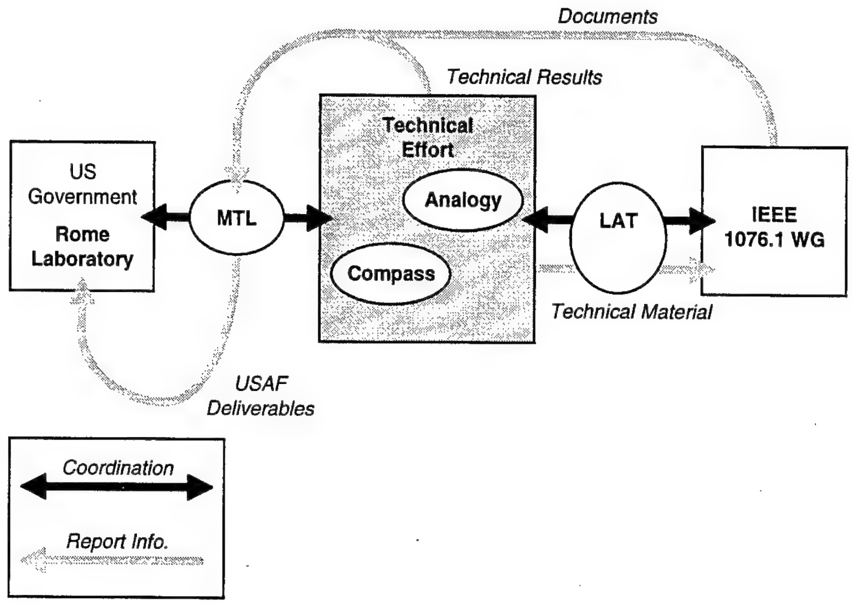

Figure 2.3.1-5: Information Flow Necessary to Produce the Deliverables

The effect of having to coordinate beyond the boundaries of the AHDL contract and to subject ourselves to schedules set by outside entities resulted in delays in deliverables and the need for an extension to the contract. These effects are illustrated in Figure 2.3.1-6.

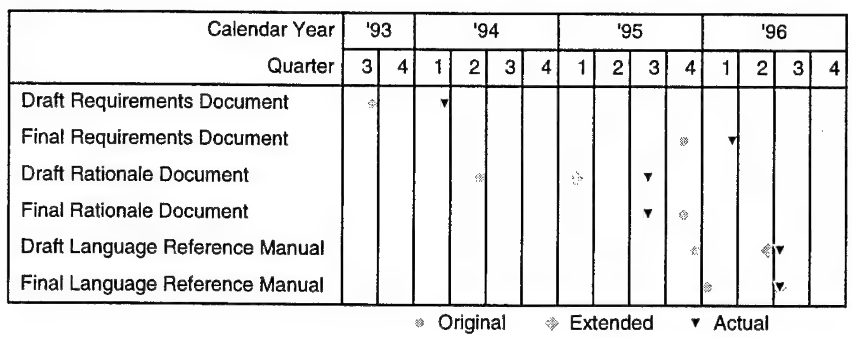

Figure 2.3.1-6: Effects of External Information Needs and External Schedule Dependency upon the AHDL Project Deliverables

Solution: We really found no solution to this challenge, except to manage the situation as best we could, through extensions and adjustments to the contractual schedule. The copyright issue needs to be addressed for future government contracts of this nature.

Challenge 4 - Producing Deliverables: As well as the scheduling of deliverables, we encountered a challenge in producing them. This challenge was a function of trying to serve "two masters," the USAF and the IEEE. Both organizations, having the common goal to develop the VHDL-AMS language, had requirements for certain data items. The IEEE had already produced a Design Objectives Document (DOD), at the inception of this project. Ultimately, the goal was to produce a Language Reference Manual to submit for balloting within the IEEE standardization process. Interim deliverables required by the contract included a Language Requirements Document and a Language Rationale Document. The IEEE also required these interim documents, which would serve as supporting background for the constructs and semantics specified within the LRM, for reviewers of the LRM to consider in their balloting.

Production of each deliverable was a challenge in itself, but the fundamental one was that of trying to extract the information from both the contractual effort and that of other WG participants, and provide it to the USAF in the specified format. The information available from the WG was continually in a state of flux, and we would no sooner assume that we had current information than we would discover that some new revision had occurred. Basically, we were trying to hit a moving target, and the Language Requirements and Rationale documents we delivered represent their state at the time we delivered them, and not necessarily a final version. However, they did serve their purpose to the WG, providing a mechanism for assimilating supporting technical detail behind the LRM.

Solution: By the time we reached the point of producing the LRM, we realized a solution. This was simply *not* to attempt to extract information from the WG and form a document while the WG was working on their next revision. Rather, we provided technical information to the WG, let them produce the LRM in their format, and incorporated their document, with appropriate credits given, into the deliverable document to the USAF. By eliminating the dual information flows, as we illustrate in Figure 2.3.1-7, we essentially let the IEEE handle the document configuration management, and used their product as the deliverable. As such, we avoided having two LRMs - a USAF version and an IEEE version.

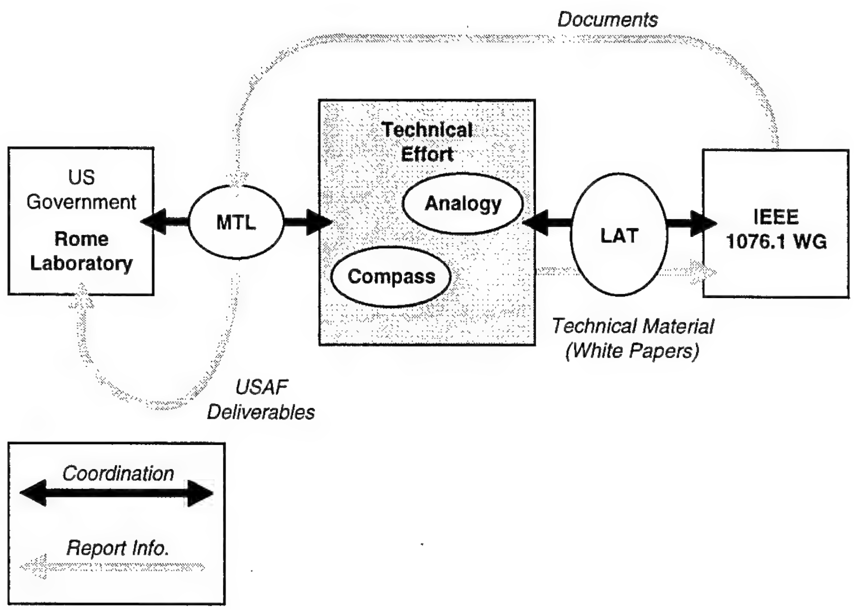

Figure 2.3.1-7: Proper Information Flow to Produce Deliverables

Challenge 5 - Keeping a Program Manager: A complicated and logistically-complex contractual effort is best served by a consistent, focused management team, and in particular, a dedicated program manager. We understand this principle, but failed to apply it to the AHDL effort. In total, we used five different program managers over the approximately 2.5-year duration of the program. Figure 2.3.1-8 illustrates the tenures of these program managers and their levels of support (hours) which were applied to the effort, by calendar quarter.

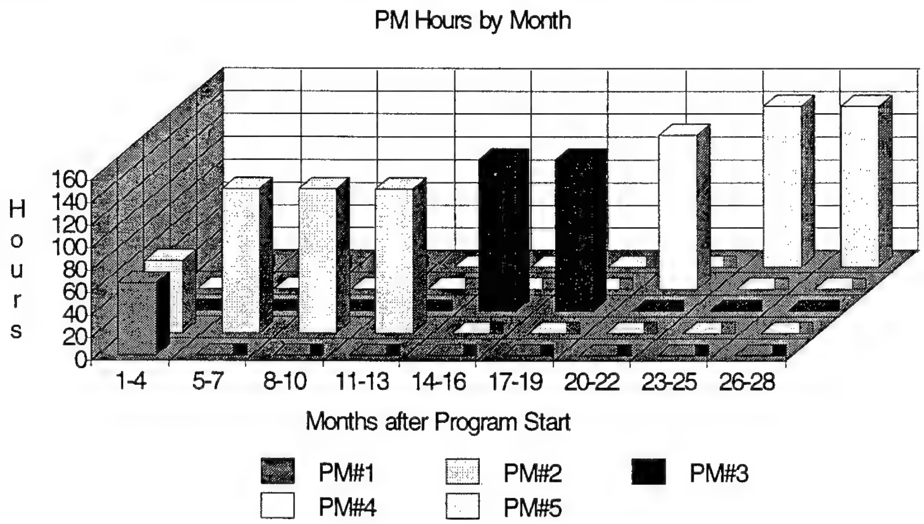

Figure 2.3.1-8: Program Manager (PM) Participation (hours) on the AHDL Program

Solution: While we realized this was a problem, we did not actually solve it. No doubt, efficiency and effectiveness suffered due to new program managers continually having to learn the program, only to depart in a short while. However, despite this inconsistency, reasonable results from the program were obtained, as we describe in Section 2.3.2.

In ***summary of our management approach and challenges***, the approach was fundamentally viable (although not optimally executed); all the challenges were either solved or at least understood well enough to preclude their occurring again in future programs, and a LRM was produced.

2.3.2 Language Development Results

The best approach to assessing results from a project is to evaluate how well they served to accomplish or achieve the goals and objectives of the program. Hence, we address our results in this context. In Section 1.3, we asserted that the overall *goal* of the AHDL program was to:

Accelerate the definition of analog and mixed-signal extensions to VHDL, through coordination with, and support for, the IEEE standardization process.

The specific objectives were to:

1. *Develop the VHDL-AMS definition (the LRM),*
2. *Coordinate with the IEEE for standardization, and*
3. *Mitigate risk (to ensure a usable, successfully-balloted standard).*

We now summarize our results in the context of these items.

Overall Goal - Accelerate the definition of VHDL-AMS: The AHDL contract certainly accelerated this definition. Rome Laboratory funding permitted two key technical contributors, Ernst Christen of Analogy and Ken Bakalar of Compass, to spend significantly more time preparing technical concepts and language constructs for inclusion in the LRM, than they would have under a voluntary basis. It is not possible to quantify the precise amount of time gained through this support.

Objective 1 - Develop the VHDL-AMS definition (the LRM): We achieved this objective by definition. A LRM was produced by the 1076.1 WG, and this project contributed significantly to its contents, through the efforts of the individuals discussed under the "Goal" topic, above. As of this writing, the LRM has not been balloted, which

we had hoped for within the contractual timeframe, but was subject to the schedules of the IEEE.

Objective 2 - Coordinate with the IEEE for standardization: We achieved this goal and performed the coordination. However, the coordination was not done effectively in the early stages of the effort. By the conclusion of the program, we understood that the best way to coordinate with the IEEE was through the LAT.

Objective 3 - Mitigate risk (to ensure a usable, successfully-balloted standard): This is a fairly intangible subject and difficult to quantify. In the sense that adding support for critical technical personnel to attend to language development efforts, we no doubt reduced the risk of a rejection upon balloting (although the actual ballot, which has not occurred yet, will be the telling event). However, the coordination problems we experienced and the challenges we discussed in Section 2.2 certainly detracted from our effectiveness in providing the risk-mitigating support. Our conclusion here is that we mitigated the risk of an unsuccessful ballot, to some uncertain degree, and could have done so more effectively.

In ***summary of our results***, they accomplished the program goal and objectives. However, we admit that they could have been more effective in doing so. In addition to the contractual deliverables, the AHDL Team members presented several symposia papers and produced various journal articles regarding VHDL-AMS, which we list in the Appendix to this report.

3.0 CONCLUSIONS, RECOMMENDATIONS, AND SUMMARY

In this section, we present our conclusions regarding the AHDL program, based upon the events and developments we described in Section 2.0. We follow then with recommendations regarding future efforts of this nature, and conclude with a summary of the effort and this report.

3.1 Conclusions

Our fundamental conclusion is that the AHDL Program accomplished its goal and achieved its objectives. However, we must also conclude that the paradigm under which we anticipated working was not effective. One of the benefits of this program is that it permitted us to adjust that paradigm and to realize a better one for Government sponsorship of technical actions in support of an open standards organization. Some more specific conclusions, in this vein, follow:

Conclusion 1 - Understanding all aspects about the Standards Committee is essential: This includes their technical, procedural, organizational, and even political motivations and goals. The support effort must integrate seamlessly with the standardization process to be effective, and can only do so with such understanding.

Conclusion 2 - Isolation of the technical effort from the non-technical aspects is essential: This program became effective only when we reached the point where our technologists were developing concepts and the (external) LAT "Tiger Team" was handling the insertion of this material into the WG's process. In reality, these particular technologists were also astute in their understanding of all the aspects of the WG, which permitted them to form concepts which had a high likelihood of being accepted. But they were not burdened with the insertion process. That is the key to the isolation - not from *understanding* the non-technical aspects, but from *having to actually deal with the insertion process.* Let the technologists develop technology and support them in integrating it into the standardization process.

Conclusion 3 - Creation of additional (from those being produced by the Standards Committee) documentation is non-productive: When we decided to incorporate the IEEE LRM as the substance of the contractual LRM deliverable, we gained substantially in efficiency. The USAF funding was enabling certain aspects of the LRM, but not all of it. The USAF has every right to require a deliverable which represents the results of their support. However, to create a

separate document is unproductive and confusing to the community at large, especially when it bears the same nomenclature as the Standards Committee document (which LRM is the real LRM?).

Conclusion 4 - Continual changes in key staff reduce efficiency: This is a foregone conclusion, and need not be elaborated further here. Continuity of key technical and management staff is of the essence.

In ***summary of our conclusions***, we understood the challenges we encountered and, although we were not necessarily able to correct some of them in this instance, they can be beneficial to future efforts. Hence, we offer the following recommendations for such endeavors.

3.2 Recommendations

Our recommendations relate generally to Government sponsorship or support of open Standards Committee endeavors. In other words, what we feel are the keys to success when an agency of the Government wishes to stimulate some standardization process under the control of an external organization. These recommendations are as follows:

Recommendation 1 - Understanding: Require the successful contractor to understand the technical, procedural, organizational, and even political motivations and goals of the Standards Committee. This can be articulated in the request for proposal's (RFP's) SOW and other requirements. Understanding only the technical and procedural aspects, in the absence of truly knowing the committee's motivations and their drivers, is insufficient.

Recommendation 2 - Execution: Require the successful contractor to demonstrate an approach by which the technical work will be accomplished with the understanding of all critical aspects, but can be insulated from procedural activities which could hinder it. If we were to propose this effort with the understanding we have now, we would propose a technical team and a WG liaison (LAT - "Tiger Team"), not a technical team and a Government liaison.

Recommendation 3 - Results and Deliverables: Require the technical effort to primarily support the standardization process, and avoid duplication of documentation with the Standardization Committee. In our view, interim and final technical reports to the Government and copies of the Standardization Committee's products, each with

an introduction regarding how the government-sponsored effort contributed to them, would be ideal. This would also avoid copyright or intellectual property rights problems between the Government and the standardization organization (such as the IEEE).

In ***summary of our recommendations***, we believe they incorporate the significant discoveries we made in the course of this project. Our sincere hope is that they will make efforts such as this one more effective in the future.

3.3 Summary

In summary of this project, it was admittedly not an easy one. Challenges were encountered, some were resolved, and the rest were documented with recommendations for avoiding similar problems in the future. Goals and objectives were met, but with less effectiveness than we would have preferred. In total, as we stated in the beginning of this report, it was a learning experience and the best instructor, as usual, turned out to be the experience itself.

Despite the challenges, the AHDL team feels that this program contributed significantly to the VHDL-AMS standardization process. Our team not only produced the majority of the technical concepts in white papers for the LRM, but also mitigated disputes, orchestrated compromises among dissenting WG factions, and initiated the LAT concept which ultimately got the whole process moving toward the standardization goal. Schedules were difficult to keep, and we certainly appreciated Rome Laboratory sponsorship, assistance, and especially *patience* as we worked our way through this project. Our efforts through the program benefited significantly from many contributors outside the program itself. Hence, we conclude our report with a thankful acknowledgment of this assistance in the next section.

4.0 ACKNOWLEDGMENTS

In the course of this effort, the AHDL Team received invaluable assistance from many individuals and organizations outside the contracted effort. Our team is grateful to have received this cooperation and support, for which we sincerely thank the following:

- The management and technical staffs of our two subcontractors, Analogy and Compass, who worked far in excess of their actual funding under this effort in a sincere desire to make VHDL-AMS a practical, useful, and universally-accepted language language.

- Our sponsor, the USAF Rome Laboratory, whose staff provided managerial and technical guidance, and exercised a great deal of patience as this effort progressed.

- Members of the 1076.1 Working Group, AVI, and the Electronic Design Automation community at large, with whom we conferred regularly on a variety of issues in the course of this program.

The companies who provided meeting facilities and refreshments for the LAT during the contract. Sometimes these companies also sponsored a lunch or dinner for the attendees. They include:

LAT#1:	July 1994, Grenoble	Anacad
LAT#2:	August 1994, Columbia, MD	Compass Design Automation
LAT#3:	September 1994, Grenoble	French Telecom
LAT#4:	November 1994, Columbia, MD	Compass Design Automation
LAT#5:	February 1995, Lausanne	EPFL
LAT#6:	April 1995, San Diego, CA	Compass Design Automation
LAT#7:	June 1995, San Francisco, CA	Mentor Graphics
	San Jose, CA	Cadence
LAT#8:	September 1995, Brighton, UK	Analogy
LAT#9:	October 1995, Boston, MA	Compass Design Automation

APPENDIX

Summary of Symposia Presentations and Articles on VHDL-AMS

The following is a summary list of symposia presentations and publications regarding VHDL-AMS, which this effort produced or stimulated. We believe these communication events served well to inform the community of the progress and ultimate benefits of the forthcoming VHDL-AMS language.

- Drager, Steven L., "Analog Hardware Description Language," Page 169, 1994 Government Microcircuit Applications Conference (GOMAC).
- Bakalar K. and Christen, E., "VHDL-A - Analog Extensions to VHDL", Proc. SCSC'96, Portland, OR.
- Christen, E., "VHDL-A - Analog Extensions to VHDL", Tutorial at 5th IEEE Power Electronics Workshop, Portland, OR.
- Christen, E. and Damon, D., "Introduction to VHDL-A Part 2: Continuous and Mixed Continuous/Discrete Aspects", invited paper, CACSD'96, Dearborn, MI.
- Christen, E. and Bakalar, K., "VHDL 1076.1 - Analog and Mixed-Signal Extensions to VHDL", invited paper, EuroVHDL'96, Geneva, Switzerland.
- MTL Systems, Inc. "AHDL Contract award." Press release submitted to 34 trade journals, magazines, and technical newspapers. August, 1993.
- Christen, E., "Interaction between Language and Tools." Presented to the European Working Group, Hamburg. September, 1993.
- Antao, A., Christen, E., Rhodes, G., and Saleh, R., "Analog Hardware Description Languages." CICC. May, 1994.
- Christen, E. (Provided material for article) "Analog Hardware Description Languages." Article in February or March issue of *New Electronics* (British). December, 1993 (Submitted).
- Christen, E., Krolikoshi, S., Liebmann, P., Shi, R., and Zhou, W. "VHDL-A Tutotial." ASIC '94.
- Barton, D., Christen, E., Krolokoski, S., and Zhou, W., "Panel Discussion on VHDL-A and MHDL Issues." VIUF '94.
- Christen, E. and Vachoux, A., "Modeling in VHDL-A: Devices, Networks, and Systems." *Current Issues in Electronic Modeling - Modeling in Analog Design.* August, 1994.

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